OSSE OBSERVATIONS OF THE ULTRALUMINOUS INFRARED GALAXIES ARP 220, MRK 273, AND MRK 231

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ABSTRACT

We report results of soft gamma-ray observations of the ultraluminous infrared galaxies Arp 220, Mrk 273, and Mrk 231 in order to test whether the infrared radiation from these sources originates from buried active galactic nuclei (AGNs). Only upper limits are measured, implying that the emergent soft gamma-ray luminosities are 1-2 orders of magnitude smaller than the infrared luminosities. Monte Carlo simulations of radiation transport through tori are used to infer the minimum column densities $N_{\rm H}$ required to block transmission of soft gamma-rays from a buried AGN, assuming that spectra of AGNs in such sources are similar to those of radio-quiet quasars. Lack of measured gamma-ray emission provides no supporting evidence for the existence of buried AGNs in these galaxies, but is consistent with an origin of the infrared luminosity from starburst activity.

Subject headings: galaxies: active — galaxies: individual (Arp 220, Mrk 273, Mrk 231) — galaxies: infrared — gamma rays: observations

1. Introduction

The enormous infrared luminosities ($L_{\rm IR} \gg 10^{10} L_\odot$) discovered in merging galaxies could originate from enhanced fueling of supermassive black holes surrounded by large column densities of dust and gas, dust heated by starburst activity, or galactic winds driven by starburst activity or the kinetic energy of colliding galaxies (e.g., Soifer et al. 1984, Sanders et al. 1988a). Detection of time-variable high-energy radiation from ultraluminous infrared ($L_{\rm IR} > 10^{12} L_\odot$) galaxies, or ULIGs, would prove the existence of AGNs in these systems and support the interpretation that quasar activity is related to mergers (Sanders et al. 1989). If vigorous star formation or galactic winds rather than nuclear activity produce the infrared emission, significantly less hard X-ray and soft gamma-ray emission is expected (Rephaeli et al. 1991; Rephaeli, Ulmer, & Gruber 1994). Photons with energies $\lesssim 10$ keV are attenuated by photoelectric absorption in Solar composition material with hydrogen column densities $N_{\rm H} \gtrsim 10^{23}$ cm^{-2}. Compton scattering opacity dominates photoelectric absorption at photon energies $\gtrsim 10$ keV, but the Klein-Nishina decline in the Compton cross section above ~ 100 keV makes the escape of higher-energy photons more probable. Gamma-ray observations therefore provide the best means for detecting a dust-enshrouded AGN (see, e.g., Krolik, Madau, & Zycki 1994).

Here we report observations of Arp 220, Mrk 273, and Mrk 231 using the Oriented Scintillation Spectrometer Experiment (OSSE) on the *Compton Gamma Ray Observatory* (*CGRO*). These three ULIGs are among the most luminous galaxies within 200 Mpc at any wavelength, with bolometric luminosities almost two orders of magnitude higher than ordinary spiral galaxies and similar to that of quasars. All three galaxies show signs of interactions and mergers, for example, a double nucleus in Arp 220, a jetlike protusion in Mrk 273 probably due to a disk distorted by tidal effects, and tidal tails in Mrk 231. Large quantities of molecular gas, which are necessary to fuel AGNs or produce vigorous

starburst activity, are found in all three systems. Signatures of Seyfert-like nuclei are found in Mrk 273 and Mrk 231, with the latter source displaying Hα line widths characteristic of a Seyfert 1 nucleus (for a recent review, see Sanders & Mirabel 1997).

Table 1 gives the infrared luminosities, redshifts, and distances of Arp 220, Mrk 273, and Mrk 231, along with the measured upper limits for the ratios of the 50-200 keV gamma ray luminosities to the 8-1000 μm infrared luminosities. Our non-detections place limits on the luminosity of the central source and the column density of intervening gas. We describe the observations in §2, and in §3 we construct multiwavelength spectral energy distributions of these galaxies. Our Monte Carlo simulation of a nuclear source surrounded by a gaseous torus is described in §4, and the implications of the observations are discussed in §5.

2. Observations

OSSE, one of four instruments on *CGRO*, is designed to detect gamma rays in the $0.05 - 10$ MeV range. OSSE comprises four independent phoswich spectrometers of identical design that are each actively shielded and passively collimated. Tungsten collimators define a $3.8^\circ \times 11.4^\circ$ full-width at half-maximum gamma-ray aperture. Table 2 summarizes the OSSE observations, plotted in Fig. 1, of the three ULIGs observed to date. The upper limits for the fluxes in the 50 – 100 keV and 100 – 200 keV energy ranges are given at the 95% (2σ) confidence level, assuming an intrinsic source spectrum with photon spectral index $\alpha = 2$. The upper limits are constant within $\approx 20\%$ for $1 \lesssim \alpha \lesssim 3$. Upper limits in the 200 – 400 keV and 400 – 700 keV ranges are also shown in Fig. 1, but are much less constraining than the lower energy data for typical AGN X-γ ray spectra with $\alpha \approx 2$.

The spectra in the sample were analysed uniformly, with similar data-selection criteria applied to all observations according to the procedures described by Johnson et al. (1993).

Quadratic interpolation in time among the measured background intervals is used to estimate the background during the source observation. Standard background offsets of 4.5° on either side of the source positions along the detector scan plane were used. The background estimates are then subtracted from the associated source accumulations to form two-minute difference spectra. These spectra are further screened for environmental effects and transient phenomena. Screened 2-minute spectra are then summed into daily average spectra and finally into spectra averaged over the entire observation interval or, as in the case of Arp 220, the entire set of observations.

3. Multiwavelength Spectra

Figure 1 shows multiwavelength $\nu L_\nu = 4\pi d_L^2 \nu F_\nu$ spectra of the three ULIGs observed with OSSE, including the 2σ upper limits derived in the present analysis. Values of νL_ν are derived assuming isotropic source emission with a luminosity distance $d_L = 2c[z + 1 - (z + 1)^{1/2}]/H_0$, appropriate to a critical density cosmology with zero cosmological constant. We use a Hubble constant $H_0 = 75$ km s^{-1} Mpc^{-1}. The radio, 1250 μm, submillimeter, and infrared and optical data are from Condon et al. (1991), Carico et al. (1988), Rigopoulou et al. (1996a), and Sanders et al. (1988a), respectively. The 0.1-4.5 keV *Einstein* data for Arp 220 are from Eales & Arnaud (1988), and the *ROSAT* data for Mrk 273 in the range 0.1 - 2.0 keV and for Mrk 231 in the range 0.1-2.4 keV are from Turner, Urry, & Mushotzky (1993) and Rigopoulou et al. (1996a), respectively. *HEAO* A-1 upper limits in the 2-10 keV range are from Rieke (1988), and additional data for Arp 220 are from Rigopoulou et al. (1996a), who also list the beam sizes for the different detectors.

As can be seen from Figure 1, ULIGs show an extraordinary feature in their νL_ν spectra peaking near 100 μm. The upper limits to the gamma-ray luminosities are $\sim 1-2$ orders of magnitude less than the infrared luminosities $L_{\rm IR}$, but are also ~ 2 orders of magnitude

greater than the soft X-ray luminosities. The $\sim 10^{17}$ Hz X-rays are probably from hot gas driven by starburst activity or from AGN emission scattered by high latitude gas. A direct nuclear origin would require a low column density, implying an AGN luminosity orders of magnitude less than the IR luminosity, in which case a dust-enshrouded AGN could not be the primary IR power source.

4. Monte Carlo Simulation of Photon Transport

We test whether the IR luminosity in these sources originates from an AGN surrounded by large columns of gas and dust. The Monte Carlo model simulates a central source of continuum radiation surrounded by a uniform torus with circular cross-section. The spectrum of the central source is represented by a two-component accretion-disk spectrum of the form

$$\dot{N}(E) = k_1 E^{-2/3} \exp(-E/E_1) + k_2 E^{-\alpha} \exp(-E/E_2) H[E - E_1] \ , \qquad (1)$$

where $H[E - E_1] = 1$ if $E > E_1$ and $H[E - E_1] = 0$ otherwise. The first term on the rhs of equation (1), which we denote $\dot{N}_1(E)$, represents the cool, optically thin Shakura-Sunyaev spectrum thought to produce the enhanced UV ("big blue bump") emission observed in Seyfert galaxies and quasars. The second term, which we denote $\dot{N}_2(E)$, represents the X-ray and gamma-ray emission observed from such sources. The normalization of the components is given by the condition

$$L_i = \int_0^\infty dE \cdot E \cdot \dot{N}_i(E) \ , \ i = 1, 2 \ . \qquad (2)$$

Defining the total luminosity $L_{\rm tot} = L_1 + L_2$ and $f = L_1/L_2$, we find that the unabsorbed X-ray and gamma-ray νL_ν spectral component is given to good approximation by

$$(\nu L_\nu)_{X\gamma} \cong \frac{L_{\rm tot}}{(1+f)[\Gamma(2-\alpha) - \frac{u^{2-\alpha}}{2-\alpha} + \frac{u^{3-\alpha}}{3-\alpha}]} \, (\frac{E}{E_1})^{2-\alpha} \exp(-E/E_2) \ , \qquad (3)$$

provided that $\alpha < 2$ and $u \equiv E_1/E_2 \ll 1$.

We choose $E_1 = 30$ eV for the cool outer blackbody spectrum, $\alpha = 1.9$ for the photon spectral index of the X-γ component, and consider two values for E_2 based on OSSE observations of Seyfert 1 galaxies (Gondek et al. 1996), namely $E_2 = 100$ keV and 400 keV. We assume solar abundances for the neutral torus material using the photoelectric absorption cross-sections of Morrison & McCammon (1983) and the full Klein-Nishina cross section (see Chiang, Dermer, & Skibo 1997 for a full discussion of the model). Our conclusions are only weakly sensitive to α between 1.5 and 2, to E_2 in the range 50 keV -1 MeV and to the value of E_1, provided that $\alpha < 2$.

The emergent spectra are generated from escaping photons which have directions within $5^\circ.7$ of the equatorial plane of the torus. Results are plotted in Figure 2 in the form $\nu L_\nu(1+f)/L_{\rm tot}$ suggested by equation (3). The torus opening angle is 45° in Figure 2; results for torus opening angles between $\approx 0^\circ$ and 60° degrees differ at most by a factor of two at $N_{\rm H} = 10^{25}$ cm^{-2}, and by less at $N_{\rm H} \lesssim 10^{25}$ cm^{-2}. For comparison with data, we identify $L_{\rm tot}$ with $L_{\rm IR}$ given in Table 1; in other words, we test the hypothesis that the IR luminosity originates from a buried AGN. We let $f = 9$, based on the results of Elvis et al. (1994) for the mean radio-quiet quasar and Seyfert energy distributions.[1] Thus 10% of the total AGN luminosity is emitted in the X-γ component.

The histograms in Fig. 1 show the $N_{\rm H} = 10^{24}$ cm^{-2} simulations overlaid on the νL_ν spectra of the ULIGs observed with OSSE for $E_2 = 100$ and 400 keV. Column densities

[1]The average and standard deviation of the ratios of the 0.1-1 μm and 1-10 keV luminosities for the 19 radio-quiet and Seyfert galaxies in the Elvis et al. sample are 7.4 and 3.8, respectively. The Elvis et al. results imply that $\gtrsim 95\%$ of such sources have $f \lesssim 15$, although the bolometric correction adds additional uncertainty.

$N_{\rm H} > 10^{23.5}$-10^{24} cm^{-2} are necessary to agree with the hard X-ray upper limits (Rieke 1988) for our standard spectrum. Strong constraints on the nature of the central source and obscuring column are provided by soft gamma-ray observations of Arp 220. Either the column density $\gtrsim 10^{25}$ cm^{-2} or, if $N_{\rm H} \lesssim 10^{24}$ cm^{-2}, then $\gtrsim 80\%$ of the total $L_{\rm IR}$ from Arp 220 is produced by non-AGN activity. The constraints on AGN activity in Mrk 273 and Mrk 231 are weaker than for Arp 220.

5. Discussion and Summary

Determining the source of the far-infrared radiation in ULIGs is important for questions of galaxy and quasar evolution. Ultraluminous IRAS galaxies seem to provide the clearest observational link between galaxy mergers and nuclear activity (Stockton 1990). It has long been known that galaxies with active nuclei have large infrared luminosities (Rieke & Low 1972), and it has been argued that ULIGs are the parent population of quasars (Soifer et al. 1986; Sanders et al. 1989). The coincidence between the bolometric luminosities of ULIGs and the luminosities of bright Seyfert galaxies (Sanders et al. 1988b) suggests that the infrared emission from these galaxies is reprocessed UV and X-radiation emitted by active galactic nuclei.

One possible explanation for the non-detection of gamma-rays from Arp 220, Mrk 273, and Mrk 231 is that the AGNs are hidden behind a very large column of gas with $N_{\rm H} \gtrsim 10^{24}$ cm^{-2}. The total mass of gas is limited, however, by observations at other wavelengths. Dynamical masses inferred from observations of Arp 220 require that the gas mass not exceed $\sim 2 \times 10^{9}$ M$_\odot$ within 350 pc (Shier, Rieke, & Rieke 1994), implying that $N_{\rm H} \lesssim 3 \times 10^{23}$ cm^{-2} for a covering factor of one. Observations of millimeter wave CO emission suggest that the gas mass in Mrk 273 is not more than 10^{10} M$_\odot$ for Mrk 273 (Rigopoulou et al. 1996b). As the gas distributions are typically a few hundred parsec

in extent (Scoville et al. 1991), the implied column density is $\lesssim 2 \times 10^{24}$ cm^{-2}, again assuming uniform covering. In the case of Mrk 231, a gas mass $\approx 3.4 \times 10^9$ M$_\odot$ is measured within a sphere of radius 420 pc (Byrant & Scoville 1996). The molecular gas must be distributed in a disk with additional scattering from high latitude gas to account for the spectropolarimetry observations of Smith et al. (1995) and the 2 magnitudes of visual extinction inferred from optical reddening of continuum and line emission (Boksenberg et al. 1977). Rudy et al. (1985) find that $N_{\rm H} \sim 10^{22}$ cm^{-2} from spectroscopy of Na in Mrk 231, which is consistent with measured absorption-line features characteristic of broad absorption-line QSOs (Smith et al. 1995), which are found to have column densities $\sim 10^{23}$ cm^{-2} (e.g., Green & Mathur 1996) .

The covering factor for the gas cannot, in a statistical sense, be much smaller than 1, due to the presence of more IR-luminous galaxies than optically selected AGN in the local universe at a bolometric luminosity of 10^{12} L$_\odot$ (Schmidt & Green 1983; Soifer et al. 1987). We cannot rule out the possibility that for the specific cases of Arp 220 and Mrk 273, patchy column densities have hidden the nuclear sources of the IR radiation. The column density to the nucleus of Mrk 231 is $< 10^{23}$ cm^{-2}, so that the hard X-ray observations reported by Rieke (1988) constrain the luminosity of any buried AGN to contribute $\lesssim 15\%$ of the IR power.

To summarize, we have placed limits on the gamma-ray fluxes of the ultraluminous infrared galaxies Arp 220, Mrk 273, and Mrk 231, with 2σ upper limits in the 50-200 keV band of 3×10^{43}, 1.6×10^{44}, and 1×10^{45} ergs s^{-1}, respectively. The measured gamma-ray to infrared luminosity ratios do not provide evidence in favor of the interpretation that the ultraluminous infrared radiation is reprocessed AGN emission. We are unable to rule out the possibility that Arp 220, Mrk 273, and Mrk 231 are quite variable in gamma-rays, and that our failure to detect them is due to observing them in the low state. Additional

CGRO OSSE observations would constrain the duty cycle of putative AGN activity. Other possibilities to account for our nondetections are that patchy columns obscure our lines-of-sight to the nuclear sources in Arp 220 and Mrk 273, or that accretion-disk spectra in ULIGs are unlike other AGNs. By penetrating to column densities corresponding to $A_V \sim 5000$, the OSSE results strengthen recent *ISO* observations (Lutz et al. 1996; Sturm et al. 1996) which indicate that most ULIGs, including Arp 220, are powered by starbursts. We conclude that there is no evidence from the hard X-ray and γ-ray observations that AGNs provide the source of the far-infrared luminosity in Arp 220, Mrk 273, and Mrk 231.

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Table 1: Ultraluminous Infrared Galaxies Observed with OSSE

	$\log\,[\frac{L_{\rm IR}}{L_\odot}]^{\rm a}$	z	d (Mpc)[b]	$(\frac{L_\gamma}{L_{\rm IR}})_{\rm max}{}^{\rm c}$
Arp 220	12.19	0.0181	73	0.005
Mrk 273	12.14	0.0376	151	0.03
Mrk 231	12.52	0.0410	166	0.08

[a] $L_{\rm IR}$ is infrared luminosity between 8 and 1000 μm from Sanders et al. (1988a).

[b] $H_0 = 75$ km s^{-1} Mpc^{-1}.

[c] L_γ represents 2σ upper limits to the gamma-ray luminosity in the range 50-200 keV.

Table 2: Observing Log and Gamma-Ray Flux Upper Limits of Ultraluminous Infrared Galaxies

Source	Viewing Period	UT Date Interval		Live Time on source[a]	Photon Flux[b] (0.05 – 0.10 MeV)	Photon Flux[b] (0.10 – 0.20 MeV)
Arp 220				6.96	< 1.2	< 0.7
	519	1996 Apr 23	1996 May 07	2.73	< 1.9	< 1.2
	531	1996 Oct 03	1996 Oct 15	2.35	< 2.1	< 1.2
	604	1996 Dec 05	1996 Dec 10	0.47	< 4.8	< 2.9
	605	1996 Nov 26	1996 Dec 03	1.41	< 2.9	< 1.8
Mrk 231	604	1996 Dec 05	1996 Dec 10	0.82	< 8.4	< 5.3
Mrk 273	515	1996 Feb 20	1996 Mar 05	4.87	< 1.5	< 0.9

[a] In units of 10^5 detector-seconds.

[b] In units of 10^{-4} photons cm^{-2} s^{-1}; upper limits are 2σ.

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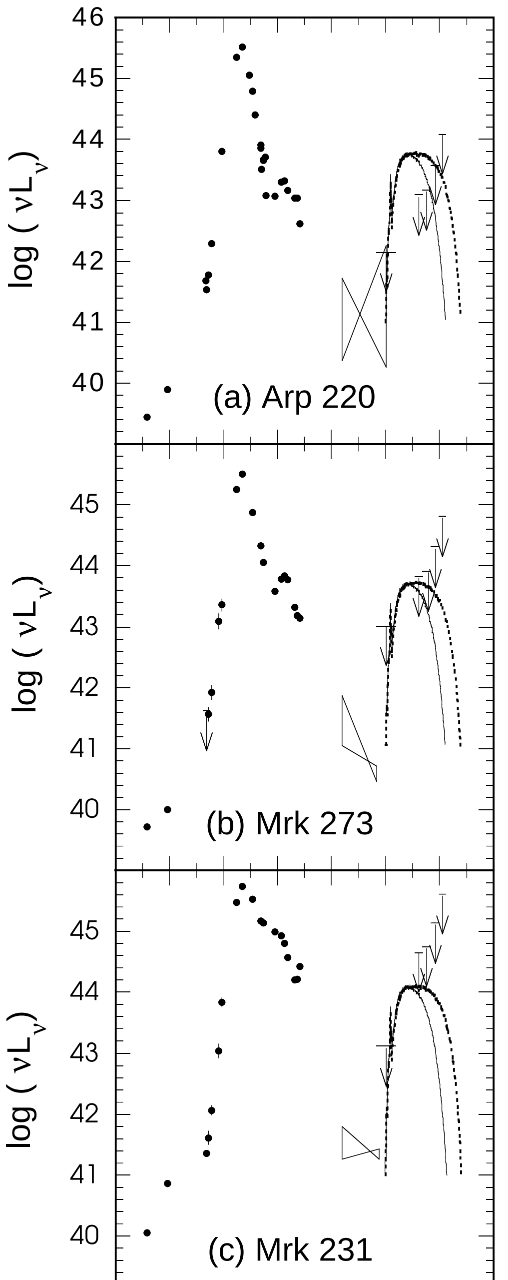
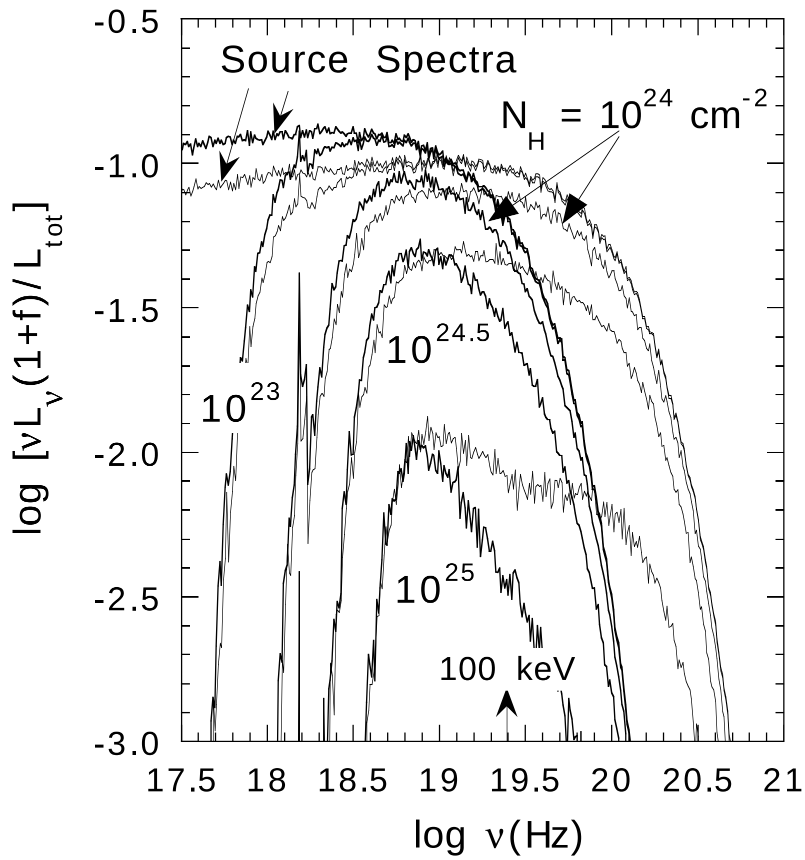
Figure Captions

Fig. 1.— Multiwavelength νL_ν spectra of Arp 220, Mrk 273, and Mrk 231. The Monte Carlo simulations show the fluxes expected if AGNs with X-ray/gamma-ray luminosities equal to 10% of the measured 8-1000 μm IR luminosity are buried behind a torus with a neutral hydrogen column density of 10^{24} cm^{-2}. The solid and dotted curves refer to source spectra with 100 and 400 keV cutoffs, respectively. See text for references to data and details of the model.

Fig. 2.— Monte Carlo simulations of photon transport from a central source located at the center of a torus with a 45° opening angle. The curves are labeled by values of the neutral hydrogen column density along a line passing radially through the torus center, and the dark and light histograms represent source spectra with 100 and 400 keV exponential cutoffs, respectively.



(a) Arp 220
(b) Mrk 273
(c) Mrk 231
log (νL_ν)
log ν



Source Spectra
$N_H = 10^{24}$ cm^{-2}
10^{23}
$10^{24.5}$
10^{25}
100 keV
log [$\nu L_\nu(1+f)/L_{tot}$]
log ν(Hz)
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
17.5
18
18.5
19
19.5
20
20.5
21